Modular and Adaptable Space Environments (MASE)

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It is NASA's mission to be the pioneers of the space frontier. With over a hundred shuttle missions and the collaboration of the International Space Station soaring over our heads in low earth orbit, the space frontier begs to be extended further. In 1968, the most powerful machine created by human hands took men to the moon for the first time. As NASA stretches its reach, it is clear that the next step is to colonize environments outside of Earth, including a long desired and more intense habitation mission to the moon. To assist in that vision, requirements for extraterrestrial habitation missions have been considered in an attempt to speed the colonization of the interesting environments in the solar system. This study attempts to develop a modular human space habitat that can quickly be adapted to multiple environments of interest using current or near future technologies. Necessities for survival were modularized and explored to create a simplistic concept of a modular and expandable habitat that is easily adaptable to the studied environments. With foreseeable applications to the simplified habitation of extreme terrestrial environments, this study also benefits those outside of the space program.

Nomenclature

A	=	area [m^2]
C	=	specific heat capacity [kJ/kg]
$\dot{m}$	=	mass flow rate [kg/s]
NTU	=	number of transfer units
P	=	power usage [kW]
r	=	distance from body to sun [m]
T	=	temperature [K]
Q, q	=	Heat transfer [W]
q''	=	heat flux [W/m^2]
U	=	heat transfer coefficient [W/m^2K]
ε	=	efficiency
ε^*	=	effective emissivity

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I. Introduction

NASA's founding and continuing mission is to expand the space frontier. Successful manned missions to the Moon and the construction of the International Space Station in low Earth orbit are testament to this vision. To truly expand the space frontier, NASA must begin looking beyond its current accomplishments and into the future. Many ideas and designs have been proposed for the colonization of Mars and the Moon. Manned missions to near earth asteroids, Venus, and the moons of Jupiter have also been investigated.

Although the colonization of space is not a new idea, we propose an idea for a universal infrastructure that will speed and simplify the business of establishing permanent bases on a variety of different celestial bodies of interest. Modular & Adaptive Space Environments (MASE) seek to become an adaptable, modular colonization systems capable of sustaining life for an extended period in any extraterrestrial environment deemed suitable for habitation. They will benefit from modular design making them quickly adaptable to a plethora of environments, cost effective, and maximally portable. Another benefit to the modular design includes terrestrial application on Earth that can be quickly applied for disaster relief situations and other hostile environments.

The idea of MASE does not only further NASA's mission statement "to extend life to there", but also supports NASA's vision "to inspire the next generation of explorers." By setting a clear goal of making even the harshest extraterrestrial environments inhabitable, MASE ventures to spark the interests and curiosity of new young NASA explorers and scientists who will be the sojourners of the visionary paths of today.

II. Motivation

Exploration is a uniquely human endeavor that has been practiced well before the dawn of modern civilization. Such notable figures as Pytheas, Zheng He, Marco Polo, Christopher Columbus, and Ferdinand Magellan have expanded the knowledge and awareness of the world around their respective societies. Today, however, the last frontiers on Earth are quickly closing, aided by advances in survival technology, satellite photography, and mobility systems. If humanity wishes to continue what those before have started, we must look skyward.
A greater understanding of our solar system and the celestial bodies within it can only help to deepen our knowledge of the universe and our home planet. For numerous decades now, humanity has sent unmanned probes to the farthest corners of the solar system, performing valuable science and learning valuable lessons along the way. Ultimately, however, it will one day be time for human beings to take the first step towards expanding outwards into the solar system.

The motivation behind Project MASE is to assist in this effort by laying the high level groundwork for the habitation systems needed to make this a reality. Along the way, MASE will compile the available information on important survival techniques and methods, including In-Situ Resource Utilization (ISRU), local radiation protection, and habitat thermal management. A better understanding of these and other items will not only be helpful when humanity moves out into the solar, but can have definitive use in the current space exploration program.

III. Habitable Places

A habitable place is an environment which has all the necessary characteristics to support human life. These necessary characteristics include a breathable atmosphere, drinkable water, a climate at comfortable temperate, food, etc. On Earth, many of these provisions are inherently available in many places. This is certainly not true of other celestial bodies, however. Elsewhere in the solar system, habitability may be defined as having the ability to sufficiently modify the local environment in order to allow humanity to live there. In many situations, "modification" involves bring along sufficient living space, air, food, and water to survive while minimizing interaction with the local environment (such as the Apollo missions to the moon). In the future, sustainable utilization of the environment may be possible, and further on, minor modification of the environment itself may allow humanity to expand into the solar system.

A number of bodies in the solar system were surveyed to determine if they may or may not be habitable within the next half-century or so. Grounds for location dismissal were focused around environmental extremes. For example, the surface of Venus is too hot for habitation, and while the upper stretches of its atmosphere may be more friendly, the engineering required to float a habitat in the atmosphere is too difficult. Other places were also considered and discarded, such as the gas giants Uranus, which is too cold, thus too difficult to colonize and Jupiter, which has far too much radiation. The following bodies are those which were studied and deemed possible for human habitation, given the proper provisions:

A. Callisto

Callisto is the fourth moon of Jupiter and is the third largest moon in the solar system, having about 99% the diameter of Mercury, though only a third of its mass. Because of its distance from Jupiter, Callisto is less affected by Jupiter's magnetosphere and has far lower radiation levels than the inner moons. Due to the low radiation levels, Callisto has long been considered the most suitable place for a human base in the Jovian system.

Callisto is heavily cratered and very old. Its surface does not show any markings that would suggest the presence of subsurface processes such as plate tectonics and volcanism. The surface of Callisto is composed of equal amounts of rocks and ices including water ice, carbon dioxide, silicates, and organic compounds. The Galileo spacecraft revealed that Callisto may have a small silicate core surrounded by a subsurface ocean of liquid water at depths greater than 100 km.

Callisto is surrounded by an extremely thin atmosphere of carbon dioxide and molecular oxygen as well as an intense ionosphere. Surface temperatures range from a minimum of 80 K to a maximum of 165 K and the surface gravity is 1.234 m/s^2.

B. Ceres

At 950 km in diameter, Ceres is the smallest dwarf planet in the solar system and the only one existing in the asteroid belt. It is speculated that Ceres consists of a mixture of water ice, carbonates, and clays. With a rocky core and an ice mantle, it is also thought that Ceres harbors a liquid ocean underneath its crust. Its position in the asteroid belt, low escape velocity, and the possible abundance of water make it a potential habitation area and strategic location for expanding human exploration to the outer planets. Living on Ceres is complicated by increased chance of asteroid collisions, extreme thermal cycling (mean temperature of 167 K, max temperature of 239 K), and lack of solar radiation, atmosphere, and magnetic field.

C. Europa

Europa is the smallest of the Galilean satellites of Jupiter. It is slightly smaller than Earth's Moon with a surface gravity of 1.3 m/s^2. Europa is subjected to large amounts of radiation from the Sun and from Jupiter's magnetosphere. Europa is of scientific interest because it is suspected that an ocean of liquid water lies beneath the moon's crust. This liquid ocean would explain the lineae (dark streaks) covering the icy surface. Because of its eccentric orbit, Europa's interior is heated by tidal flexing. The presents of heat and the possibility of liquid water makes the moon a good candidate for supporting life. A human presence on this moon would greatly benefit the exploration of this subsurface ocean. Exploratory robots could be more easily deployed into the ocean by hand. They could also be controlled in real time, improving their usefulness. Resources available for ISRU include water ice on the surface and the very thin oxygen atmosphere.

D. Ganymede

Ganymede is the largest satellite of Jupiter with a diameter of 5268 km. It is composted of equal parts water ice and silicate rock. Thought to have an iron-rich liquid core, it is the only satellite in the solar system to have its own magnetosphere. In addition, it also has a very thin (1 μP) oxygen atmosphere. About 200 km below the crust, Ganymede is believed to have a salt water ocean. With similar features to extreme regions of Earth, exploring Ganymede for life as well as looking for clues about its past and future could reveal more about our own watery home. The extreme thermal cycling (70 K to 152 K), possible geological activity, and radiation levels 80 times higher than that of Earth are all complications to take into consideration.

E. Mars

Mars is a cold desert world. It is half the diameter of Earth and has the same amount of dry land. Like Earth, Mars has seasons, polar ice caps, volcanoes, canyons and weather, but its atmosphere is too thin for liquid water to exist for long on the surface. There are signs of ancient floods on Mars, but evidence of water now exists mainly in icy soil and thin clouds. Using the Martian atmosphere, oxygen could be produced. Water could also be utilized, as large supplies can be found under the surface.

F. Moon

The moon is Earth's only natural satellite and is thought to be 30 to 50 million years old. Because the Moon lacks an atmosphere, the surface is riddled with the markings left behind by meteor impacts. The composition of lunar regolith (Moon's soil) is composed mainly of silica. Additionally there are fair amounts of alumina, lime, iron oxide, and magnesia with traces of titanium dioxide, sodium oxide, and ice. The gravity on the Moon is approximately one sixth of the gravity on Earth, and the temperatures range from 100K to 390K on the equator. The

Moon is the only other planetary body that people have visited thus far, and is the most well-studied and documented. This is why it is often considered as the easiest place to set up a permanent colony.

G. Phobos

Phobos is the first and largest moon of Mars. This moon is small and irregularly shaped, with a mean radius of only 11.1 km and a surface gravity of 0.008 m/s^2. Phobos has long been considered a good landing site to study Mars or perhaps even be a landing port on the way to Mars. Phobos would be considerably less difficult to land on than landing directly on the surface of Mars due to the lack of an atmosphere. Phobos is a C-type body without an atmosphere, therefore having little in the way of in-situ resources.

H. Titan

Titan is the largest moon of Saturn and is the only known object other than Earth where stable bodies of surface liquid have been found. This moon is composed primarily of water ice and rocky material . The dense atmosphere on Titan is composed primarily of nitrogen, but also has up to 5% methane. The surface of Titan is geologically young, as the surface is relatively smooth. A few mountains and possible cryovolcanoes have been discovered on the surface of Titan. The gravity on Titan is 1.352 m/s^2 with a surface pressure of 146.7 kPa. The temperature remains relatively constant at 93.7 K.

I. Earth – Hot Desert

The desert environments found on earth are very extreme, inhospitable areas. Habitats existing in these areas face similar challenges to those constructed on foreign planets. Thermal management of hot and cold temperature extremes, rugged terrain, and limited usable resources are some of the challenges that these environments present. Earth deserts can reach temperatures of 45 degrees Celsius and dip as low as 0 degrees Celsius. Sand and dust can often damage equipment and vehicles especially when propelled by strong winds and sandstorms. Very little vegetation, animals, and water can be found in these harsh environments. However, deserts often possess great amounts of mineral resources such as nitrates, borates, uranium, gold, silver, and oil. These sometimes rare natural resources provide an effective motivation for inhabiting such a hazardous location. Deserts also offer significant scientific motivation because organisms found here are likely to be similar to organisms found on other planets or moons.[1]

J. Earth - Rainforest

Earth's rainforests are valuable locations for studying life here on earth. A high-tech base within a rainforest would greatly improve productivity of scientists. Rainforests are wet humid environments. Tropical temperatures can be expected. Water is a widely available commodity that could be captured from rain fall on a daily basis. Other resources within the rainforest, such as wood and food, are widely available, although a scientific outpost would likely be trying to minimize their footprint. Exposed equipment may be damaged by rainfall, animals, and vegetation. Proper precautions should be taken.

K. Earth - Antarctic

Antarctica is often thought to be the cruelest environment on Earth, as it is the largest, coldest, and windiest desert on the planet. Temperatures in the Antarctic range from 193 K in the interior to 288 K near the coast. Due to the extreme conditions, Antarctica is sometimes used as an outpost for NASA research for missions to Mars for example. Not surprisingly, the Antarctic desert provides a fairly similar cold and dry environment to that of Mars, and experiments tested in Antarctica as opposed to directly on Mars, are on the order of a few magnitude less cost. Researchers have semi-permanent outposts currently in Antarctica, though it is still a great place to consider for a modular habitat.

IV. System Requirements

Based on the planet and moon environments that are deemed habitable, a list of necessary system requirements was generated. These requirements are broken down into the most basic survival needs for each environment. Many systems changed based on the environment they are in due to things such as gravity levels, temperature differences, and radiation levels. The following sections discuss each of these basic systems. Additionally, there are basic system needs that will be the same, or very similar, from habitat to habitat. Some of these systems are also addressed below. Once these basic systems are designed and developed, they can be integrated to form basic modules, which in turn can be integrated to form entire habitats.

A. Communications

Each colony will take advantage of the NASA SCaN (Space Communications and Navigation) Deep Space Network to communicate back to Earth via a satellite orbiting the body of habitation. This satellite will take advantage of the newly developed optical communications network and will be able to send and receive data at rates up to 100 Mbps for planetary missions and up to 1.2 Gbps for lunar missions. The colony itself will use wireless communication between modules, taking advantage of current technologies in small household wireless routers. These routers will be connected to a computational cluster that will manage all necessary data for planetary communications, extraplanetary communications, experimental work, etc. This cluster will be housed in its own module that contains a large transmitter to communicate with the orbiting satellite. Back-up, lower quality, transmitters will be housed in each module in case of main transmitter failure. This system will not require modification based on destination.

B. Environmental Hazards

There is a need to investigate environmental hazards in the preparation for prolonged habitation. Each of the planned locations was considered when determining what hazards may be faced. Table 1 summarizes the results of this study. Some hazards pose no threat due to the inherit design of the modular capsules. Other hazards create design considerations for the system. From the hazard study, the module needs in addition (to previously mentioned systems):

1. way to securely attach to the ground. This can be accomplished by drilling into the surface and securing the feet of the module.
2. securely supported sail-like structures. Specifically, the poser system radiators will need to be supported properly.
3. a micrometeoroid shield. A Stuffed Whipple Shield design will be used to cover the module.
4. maintenance access to clean and repair sensitive equipment. Dust storms may degrade the performance of radiator shields creating the need to clean them. Micrometeoroids could damage exposed equipment which would then need to be repaired or replaced.

Table 1. Environmental Hazards to Consider for each Location

Hazard	Environment Present	Avoidance Measures
Cryovolcanoes	Titan	Proper heat shielding, attach to ground
High Winds	Titan, Earth Antartic	Avoid sail-like structures, attach to ground
Seismic Activity	Titan, Ganymede, Europa, Earth	Ensure structure holds up to dynamic loads and vibrations, attach to ground
Micrometeoroids	Ganymede, Europa, Callisto, Ceres, Moon, Phobos	Proper shielding (Stuffed Whipple Shield)
Dust Storms	Mars, Earth Desert	Protect and clean sensitive equipment

1. Cryovolcanoes

Cryovolcanoes are an issue on the moon Titan. It is thought that liquid water and ammonia erupt from volcanoes onto the surface. To prepare for this threat the capsule needs to have proper heat shielding and should be securely attached to the ground.

2. High winds

High winds are issues on Titan and the Earth's Antartic region. Sail-like structures will be blown by the wind and may be damaged, or cause damage, as a result. This threat can be mitigated by avoiding sail-like structures or securely supporting.

3. Seismic activity

Seismic activity may be a hazard on Titan, Ganymede, and Europa. Earth environments should also prepare for this hazard. Since the modules are designed to withstand the extreme forced and vibrations during a rocket launch, seismic activity should pose no threat. The module should be attached to the ground to avoid tipping over.

4. Micrometeoroids

Micrometeroids are a threat on Ganymede, Europa, Callisto, Ceres, Moon, and Phobos. This is due to the lack of an atmosphere on these environments. Proper shielding from micrometeoroids will mitigate this threat.

5. Dust storms

Dust storms are a threat on Mars and the Earth's Deserts. The dust can cover sensitive equipment, degrading the systems performance. This issue can be resolved through routine cleaning and repair of affected equipment.

C. Exercise

A key factor in human health and survival on the Earth and other celestial bodies is caring for one's body through routine exercise. Regular exercise is critical in order to grow, repair, and maintain healthy bones, muscles, and ligaments. For locations on Earth, a standard exercise module can be utilized for regular exercise. The module would contain both aerobic and resistive types of exercise equipment. The three most common pieces of exercise equipment are treadmills, stationary bicycles, and resistive weight machines. The treadmill is a valuable machine because running is an aerobic exercise, but also supports good bone and ligament health by stimulation of the bones and joints through transferred ground reaction forces. The stationary bicycle acts as another aerobic machine, but also supports muscle maintenance and growth by changing the resistance levels the person has to push against. Finally, use of the weight machine supports muscle health in the upper and lower limbs as well as through the core.

For celestial bodies with gravity levels only slightly less than Earth's including Mars, the Moon, and Ganymede, similar exercise modules can be used. The stationary bicycle and weight machine are used in the same manner as on Earth, though the resistance and weight need to be increased to reach the same forces as a person would see on Earth. Due to the low gravity, the treadmill would not be as effective as it would be on Earth because the ground reaction forces would be so much lower. To counter-act the low forces, a person would have to be tethered to the treadmill to simulate gravity by pulling the person back down onto the treadmill.

Moons including Titan, Europa, Callisto, Ceres, and Phobos, which have only a fraction of Earth's gravity, would require an exercise module more like the one on the International Space Station. People would have to be tethered to the treadmill and stationary bicycle. Additionally, they would have to use high resistance on the bicycle and weight machines. The weight machines also cannot be standard weight machines due to the low gravity and would have to be beam bending or resistive band type machines. Persons would also be required to work out for longer periods of time and use other means of stimulation such as electrical or vibratory stimulation to help promote bone and muscle growth. There has been no perfect cure for muscle and bone atrophy due to microgravity, and studies are currently being done to mitigate these problems.

D. Filtration System

Current filtration systems on the International Space Station use primarily high-efficiency particulate air (HEPA) filters. HEPA filters, as defined by the Department of Energy standard, remove at least 99.97% of aerosolized particles 0.3 micrometers or larger. Higher class HEPA filters can have efficiency ratings upwards of 99.995%. The filters used on the ISS are cleaned on a weekly basis by vacuuming, and replaced as needed, which typically occurs every few months. New methods are currently being studied to increase the life of these HEPA filters and reduce the number of consumables (i.e. spare filters and waste) and reduce the necessary maintenance.

There are two basic types of filtrations systems for the different types of celestial bodies. However, there are also commonalities between filtrations systems of all the habitats. Each module will have to have a filtration system that effectively removes internal dust generation. These filtration systems can be interconnected between modules, or each module can have its own small filtration system that is run off of a small fan. The filtration systems can consist solely of the traditional HEPA filter system or include next-generation filtration regeneration systems consisting of rolling-media filters, reverse flow cyclones, screens, and electrospray filters. Any module with outside access to any of the environments will require an airlock with more powerful filtrations systems. These powerful filtration systems have higher flow rates and larger filters. The people and machines in the air locks would be required to stay in the locks with protective equipment on until appropriate contamination levels are met.

Phobos, the Moon, Europa, Ceres, Mars, Earth Rainforest, and Earth Desert would require a basic filtration system with the aforementioned features. The system would be a standard fine particulate filtration system. Callisto, Titan, Ganymede, and Earth Antarctic would require a slightly more advanced air filtration system due to the presence of water ice molecules in the air. The basic filtration system would be combined with an additional filtration system to melt out the water from the air and pass it along to the water purification system.

E. In-situ Resource Utilization

To make missions to extra terrestrial destinations feasible, all resources cannot be brought along from Earth to each colony. These extended missions, which can take up to six years in travel and habitation time, cannot be completely supplied from initial lift-off. One solution to this problem is to utilize the resources on the body of habitation to supply the habitat with necessary water, oxygen, and fuel. Just as natural resources are used on Earth, resources found on other environment can also be utilized. It is important, however, to utilize these resources in such as way as to minimize waste. This section discusses the resources which can be found in each of the chosen environments, the ways they can be utilize, and the end products received after processing.

1. Callisto

There is a large amount of water on the surface of Callisto. Satellite flybys estimate between 25 and 50% of the surface is composed of water ice by mass. The surface also contains carbon dioxide ice at the poles. It is speculated that carbon dioxide could also be gained from conversion of surface organics or the degassing of the surface. This water gained from surface matter could be further processed by electrolysis to provide H_2 and O_2. The Sabatier reaction detailed in appendix A could take surface distilled carbon dioxide and H_2 from electrolysis to provide water for crew use and methane for fuel. Furthermore, the H_2 and O_2 gained from electrolysis can be used to power fuel cells providing the crew with supplemental power and fresh water.

2. Ceres

Ceres may contain a thick mantle of liquid water and a surface of hydrated minerals. If drilling to the water mantle proves to be an impossible task, the hydrated minerals can be processed to remove water for crew utilization. The surface which is populated by carbonates or minerals containing CO_3 can be processed to remove carbon dioxide. The respiratory waste of the crew could also provide a source of CO_2. The water gained from surface matter or drilling processes could be further processed by electrolysis to provide H_2 for fuel and O_2 for fuel and crew respiration. As most of the gas in the cabin is reused, it is assumed that the need to restock the habitation module with water and oxygen will be relatively low. The Sabatier reaction could take carbon dioxide and H_2 from electrolysis to provide water for crew use and methane for fuel. Furthermore, the H_2 and O_2 gained from electrolysis can be used to power fuel cells providing the crew with supplemental power and fresh water.

3. Europa

The surface of Europa is a100 km layer water with a crust of ice. It is up for speculation whether or not beneath this thin crust is a liquid ocean. Regardless, the procurement of water on Europa is sure to be a simple and energy efficient task. The water gained from Europa could be further processed by electrolysis to provide H_2 for fuel and O_2 for fuel and crew respiration. Furthermore, the H_2 and O_2 gained from electrolysis can be used to power fuel cells providing the crew with supplemental power and fresh water.

4. Ganymede

The mass fraction of water ice on the surface of Ganymede is between 50 and 90%. The water gained from surface matter processing could be further processed by electrolysis to provide H_2 for fuel and O_2 for fuel and crew respiration. Again, the H_2 and O_2 gained from electrolysis can be used to power fuel cells providing the crew with supplemental power and fresh water.

5. Mars

Previous missions to Mars have revealed polar ice caps which contain water ice. In cooler months, these caps also contained CO_2. Water has been detected on the equatorial surface of Mars as well. These resources could be obtained from the polar caps of Mars through a melting process, if not obtained from other portions of the Martian surface and the scant atmosphere as well. As discussed previously, H_2, O_2, freshwater, and methane could be manufactured and used.

6. Moon

Many techniques have been developed by NASA for ISRU on the moon. Most pertinent to support this habitat would be the resource of water. Using developed techniques to obtain water from icy lunar regolith, H_2, O_2, power, and freshwater could be created through the processes detailed for previous surface missions.

7. Phobos

It is speculated that beneath the regolith of Phobos lies a significant reservoir of water. Habitation of any duration on Phobos is dependent on this. The porosity of Phobos is too large and the density too great for the body to not contain something thing within its pores. Water that is excavated from beneath the surface could again be used in the common processes listed above to sustain life.

8. Titan

Titan's crust is mainly composed of water ice while its thick atmosphere is largely of nitrogen and methane. Water gained from the surface of Titan as well as possibly from its cryovolcanos could be used to supply a habitation with water, H_2, O_2, and other carbon based fuels by direct utilization as well as processes detailed above.

9. Earth

It is not a question of whether or not these resources, water and carbon dioxide, exist on in the various environments, it's a matter of how to harvest them. Wells would of course be used for water in the desert, while active water collection could be used in the rainforest. Methods of defrosting, similar to those used on extra terrestrial planets could be used for water acquisition in the Antarctic climate. Carbon dioxide is abundant on this plant from human and animal respiratory waste as well as the by-product of an industrial climate and research that is currently being performed from CO_2 sequestration can be applied to its capture in these extreme environments. The main reason for gathering these resources would be for human consumption as well as fuel and power for the habitat.

F. Oxygen Production

1. Oxygen Requirements

Oxygen requirements for one crewmember of average size are 0.84 kg (about 1 kg) per day.[2] In terms of liters of oxygen, this equates to 600 liters per day, per crewmember. Calculations for various crew sizes from one to nine are given in Table 2.

Table 2. Daily Oxygen Requirements

Crewmembers	O_2 Required by Crew (L/day)
1	600
3	1800
6	3600
9	5400

2. Oxygen Production Technology: The Elektron-V System

The primary system for oxygen production will be the Russian Elektron-V that is currently used on the International Space Station. The Elektron-V provides breathable oxygen through electrolysis. Electrolysis produces oxygen by breaking down water into hydrogen and oxygen in the presence of potassium hydroxide. Potassium hydroxide is used in the process to aid in ionization.[3] The ionized form or Potassium hydroxide is shown in Equation 1

$$\mathrm{KOH} = \mathrm{K}^+ + \mathrm{OH}^- \tag{1}$$

The process of electrolysis proceeds as follows: "At the anode, negative ions of the hydroxyl group OH^- migrate towards the positive anode and discharge, releasing electrons and oxygen and forming water; while water molecules combine with the hydroxyl molecules, migrate to the cathode, oxidize, and release hydrogen.[3]" This process is shown in Equations 2 and 3.

$$4\mathrm{OH}^- + 4\mathrm{e} = 2\mathrm{H_2O} + \mathrm{O_2} \tag{2}$$

$$2\mathrm{H_2O} + 2\mathrm{e} = 2\mathrm{OH}^- + \mathrm{H_2} \tag{3}$$

Electrolysis of 1 kg (2.2 lb) of water produces 25 L of oxygen per hour. This amount is sufficient to meet the daily oxygen needs of one crewmember.[3] Table 3 lists how much water must be supplied for electrolysis and how much oxygen must be produced to meet the daily needs of various crew sizes. Water will be supplied to the Elektron-V by fuel cells as discussed in the water production section of this paper.

Table 3. Daily Water Requirements

Crewmembers	Number of Elektrons	H_2O Required for Elektron to Operate (kg and lb)	Power Consumed by Elektron (kW)	O_2 Required by Crew (L/day)	O_2 Produced (L/day)
1	1	1 kg (2.2 lb)	1	600	1900
3	1	3 kg (6.6 lb)	1	1800	1900
6	2	6 kg (13.2 lb)	2	3600	3800
9	3	9 kg (19.8 lb)	3	5400	5700

All of the oxygen generated by the Elektron-V system can be released directly into the module. Hydrogen byproduct can either be used in in-situ resource utilization or discarded as waste. Backup oxygen will be available as bottled oxygen and as solid fuel oxygen generation (SFOG) canisters. Each SFOG canister can supply the oxygen needs of one crewmember for one day.[3]

3. The Elektron-V System Specifications

The Elektron-V can generate approximately 1900 liters of oxygen per day. The system's 12 electrolysis cells each have a cell voltage of 2 V and its average power consumption overall is 860 watts (about 1 kW). The mass of the unit is roughly 150 kg (331 lb); and dimensions for the Elektron-V are 0.8 m by 0.13 m (2.62 ft by 0.43 ft). It was designed for a life of about three years.[3]

G. Power Systems

For all space environments surface fission power systems will be used to power the habitats. Fission is a reliable long term energy source requiring minimal maintenance. Technology for this power system is being developed at the Glenn Research Center.[4] The reactor uses uranium oxide (UO_2) fuel pins in a hexagonal core to generate 186 kW of thermal energy. The core is partially shielded and subcritical until the reaction is started by crew on the surface. The core will be buried in the terrestrial surface to provide additional cheap shielding. The leakage of radiation calls for the core to be isolated from the base, approximately 100 meters. Power transmission and data cables will be run between the base and the power system. NaK is used to transfer the thermal energy from the reactor through heat exchangers to four Stirling converters. The Stirling converters are water cooled by a heat radiator system. Two radiator wings 16 m long by 14 m tall reject 35 kW of heat per cycle. This radiator configuration has been designed for the Moon and Mars, and can be adapted to new environments. The Stirling converters are estimated to be 26% efficient. Using four of these engines and taking into account loss, approximately 40 kW of electric energy can be generated. Multiple systems can be utilized depending on the power requirements of the base. A diagram of this power system in a half deployed configuration is shown in Figure 1. The system is expected to provide steady power for 8 years with minimal maintenance. The mass of this system depends primarily on the size of the radiator shields and the amount of core shielding required. Total system mass for a Moon configuration is expected to be 5820 kg.

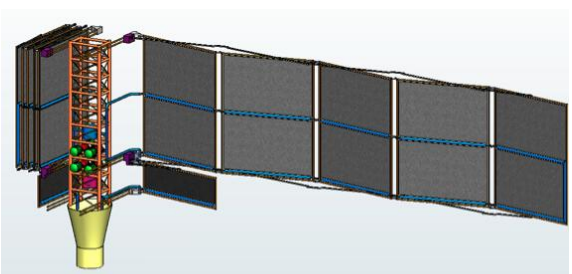

Figure 1. Surface Fission Power System Concept[4]

This power system was chosen due to its status as a developing technology and its modular nature. Modularity allows the system to be easily adaptable to all terrestrial environments being investigating. Each system can also be developed independently and at a lower cost as a result.

For earth environments, power will primarily be supplied by fossil fuel generators. Green technologies such as wind and solar power can be implemented as seen fit. Once the technologies fully develop into a reliable power system, green power systems may eventually replace the generators.

H. Radiation Shielding

One of the most challenging aspects of deep space exploration and colonization is minimizing the astronauts' exposure to radiation. While Earth and Titan present almost negligible radiation exposure, long term stays on the Moon, Ceres, Callisto, Phobos, and Mars would require adequate shielding against deep space radiation to avoid long-term health problems. Due to the plasma torus encircling Jupiter, created by the interaction between Io and Jupiter's magnetic field, the radiation shielding required for even a short-term colony on either Ganymede or Europa would be significant.

The two primary sources of deep space radiation are solar particle events (SPE) and galactic cosmic rays (GCR). SPE's are relatively rare events, and occur when the sun ejects an uncharacteristically large number of charged particles. SPE's are typically short in duration and are most likely to occur during the more active part of the sun's solar cycle. The sun goes through an 11 year cycle in which the strength of its solar wind and radiation output vary.

Galactic cosmic rays, on the other hand, are heavy, high energy ions that penetrate the heliosphere from interstellar wind. GCR's deliver a steady dose that is not severe for short durations, but can become harmful over extended periods of time. These rays are a particular challenge because they are difficult to shield against.[5]

1. Health Effects

One of the most pressing issues in the design of a radiation shield for a space habitat is set by the exposure limits for the astronauts. While completely eliminating all radiation within the habitat is most desirable, doing so would require impractically heavy radiation shields. Thus, shields would need to be designed such that they reduce the radiation exposure within the habitat to a level that poses an acceptable risk to the crew. Because human exploration beyond Earth's magnetosphere has been very limited, little is understood about the health risks associated with GCR's and SPE's.[5]

Table 4. Recommended Dose Equivalents for Organs of All Ages[5]

Exposure Interval	BFO Dose Equivalent (cSv)	Ocular Lens Dose Equivalent (cSv)	Skin Dose Equivalent (cSv)
30-day	25	100	150
Annual	50	200	300
Career	See Table 2	400	600

Most studies use the lifetime limits for LEO exposure to radiation. The direct measure of radiation intensity for GCR's and SPE's is the particle fluence, which is measured in particles per square meter. Different particles of different energies have different effects on the human body and cell transformation. The health effects of the radiation are estimated using weighted factors. Radiation exposure limits are expressed in Sieverts (Sv) or centiSieverts (cSv), which describe a given radiation environment's effect on the human body.[5] Recommended dose equivalents for organs are shown in Table 4, where BFO stands for blood forming organs. Table 5 shows the recommended whole body exposure limits for astronauts in low Earth orbit.

Table 5. Whole Body Exposure Limits for Radiation Dose for Astronauts in Low Earth Orbit

Age	25	35	45	55
Male	0.7	1.0	1.5	2.9
Female	0.4	0.6	0.9	1.6

2. Radiation Shield Concepts

A number of radiation shield concepts have been proposed. These concepts can be divided into 3 categories: electromagnetic, exotic materials, and advanced materials.[5] Electromagnetic shield concepts slow or redirect charged particles away from the colony. This type of shield has been ruled out as an option because of the massive amounts of power required to make it effective. Exotic materials concepts suggest using in-situ materials, such as making a thick lunar regolith dome to shield from the charged particles; however the design concept for a modular colony does not lend itself well to this type of shielding. Finally, the advanced materials option suggests manufacturing new materials to absorb the radiation. For this study, shielding thicknesses and materials were investigated.

The physics governing radiation via materials is complex, and still not fully understood. High charge and engery (HZE) particles associated with GCR's contain enough energy to split a nucleus of an element within the shield apart, potentially generating more high energy particles and neutrons, which can in turn increase the radiation exposure within the habitat itself. It is difficult to predict the performance of a radiation shield material because the nuclear interactions between the shield material, the environmental radiation, and the secondary products must be tracked. Diffusion of these particles through the material is also difficult and computationally expensive to predict. For such reasons, high atomic number elements are generally considered a poor choice for shielding from deep space radiation because of their high neutron content and potential to split into more charged particles. Hydrogen is considered the best element for radiation shielding, as it cannot be split.

Figure 2 shows predicted attenuation of the radiation dose equivalent and rate of cell transformation from charged particle radiation normalized with respect to the no shielding case in deep space. Materials with an atomic number below that of iron are effective at reducing the net dose equivalent within the habitat, whereas materials made with lower atomic number elements, such as water, hydrocarbons, and hydrogen, are effective at actually reducing the rate of cell transformation within the habitat. Materials such as lead increase the radiation hazard is due to the sendary nuclear interations between the material and the environmental radiation. It should also be noted that aluminum would be a very poor choice for radiation shielding because the graph on the right clearly shows that aluminum generally increases the rate of cell transformation. Thus, the 5 g/cm^2 aluminum shielding used on the space station is a poor choice for radiation shielding beyond Earth's magnetosphere.

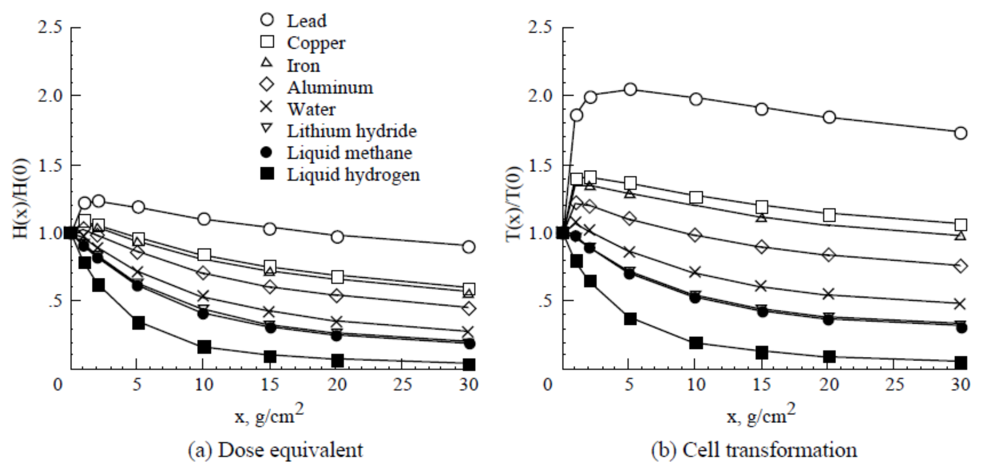

Figure 2. Shield dose attenuation (a) and rate of cell transformation (b) for a variety of shield materials

3. General Radiation Shield Requirements

Several different types of material are considered for radiation shielding, including AL2219, polyethylene, hydrogenated nanofibers, and liquid hydrogen.[6] Figures 3, 4, and 5 show dose equivalents for the Moon, Mars and Callisto. These plots were instrumental in determining required shield depth.

The necessary shield thickness is a function of the crew's age, the duration of stay, and the shield material. As a person ages, the amount of radiation they can receive increases, means that that a young astronaut, say a 20 year old male (or 30 year old female equivalent) would be the worst case scenario for shielding requirements. This leaves shielding to then be a function of time and material. To calculate the required wall thickness, the shield depths is divided by the material density. Liquid hydrogen was not considered as a viable shield material because its density is too low.

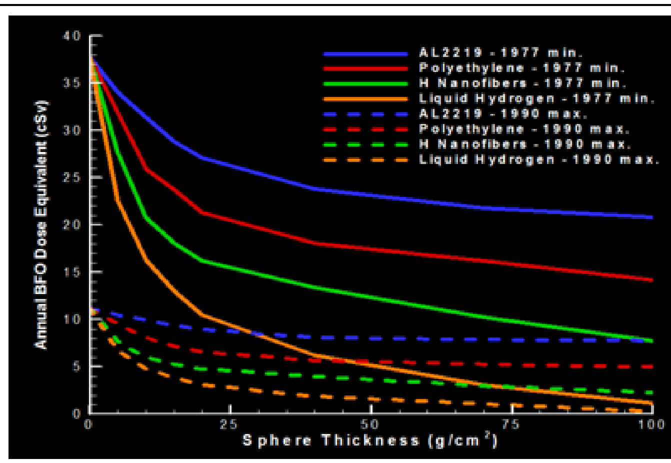

Figure 3. Habitat Dose Equivalent on Lunar Surface

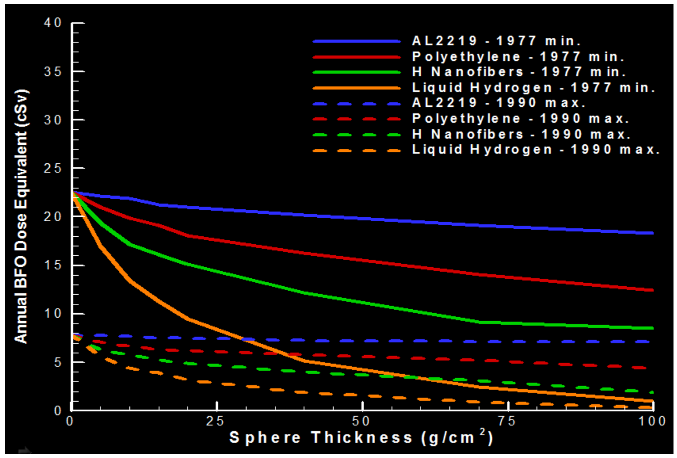

Figure 4. Habitat Dose Equivalent on Mars Surface

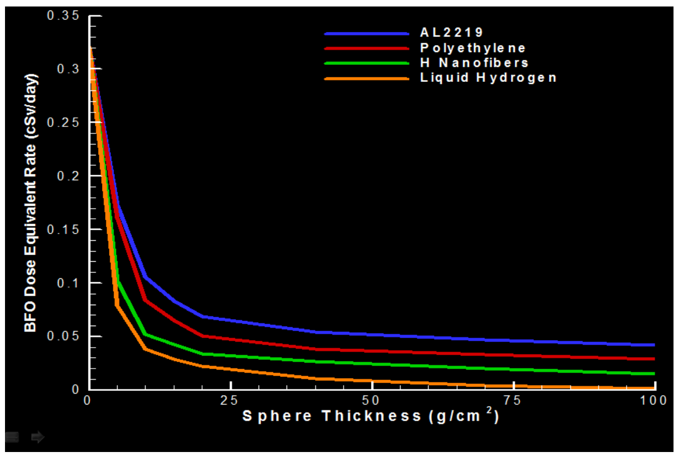

Figure 5. Habitat Dose Equivalent on Callisto

On some of the moons and planets, shielding from GCR's is not necessary in order to stay well below lifetime exposure limits. Therefore, the radiation shield thickness is governed by exposure limits to a deep space SPE. Figure 6 provides data on radiation shield effectiveness for SPE. Using this data in conjunction with the data from Figures 3, 5, and 5, the linear wall thickness for each material type can be calculated as 5.3 cm for aluminum, 11 cm for polyethylene, and 14 cm for H nanofibers. It cannot be assumed that the thinnest material is the most practical, because the mater densities vary, leading to different total masses and different assumed launch costs. This, however, is not in the scope of the project.

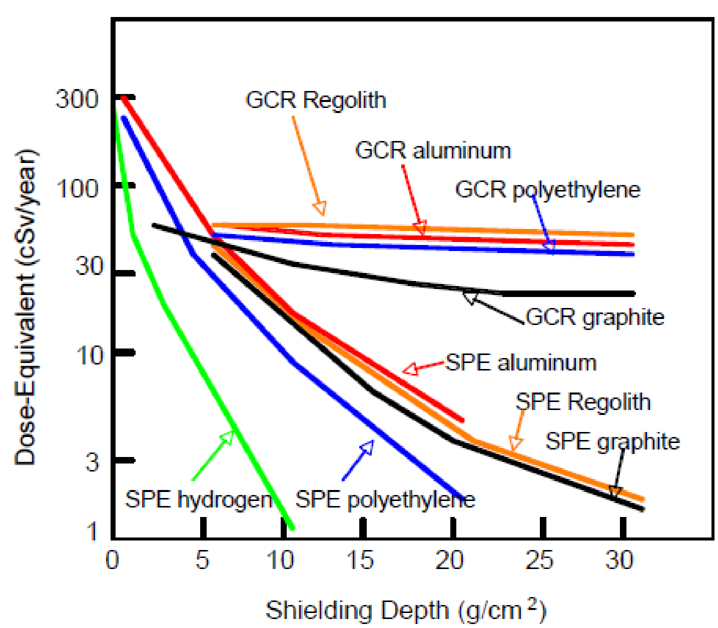

Figure 6. SPE and GCR Shielding Effectiveness

4. Moon, Phobos, and Ceres

Due to the fact the Phobos, Ceres, and the Moon all have similar composition, all lack an atmosphere, and all are located outside of geomagnetospheres, it can be assumed that they are all exposed to the same radiation levels. Data for radiation shielding on the Moon is known and will be used as the basis for calculations. As stated previously, the radiation shielding is a function of material and duration of stay. Figure 7 shows the necessary shielding thicknesses for these parameters.

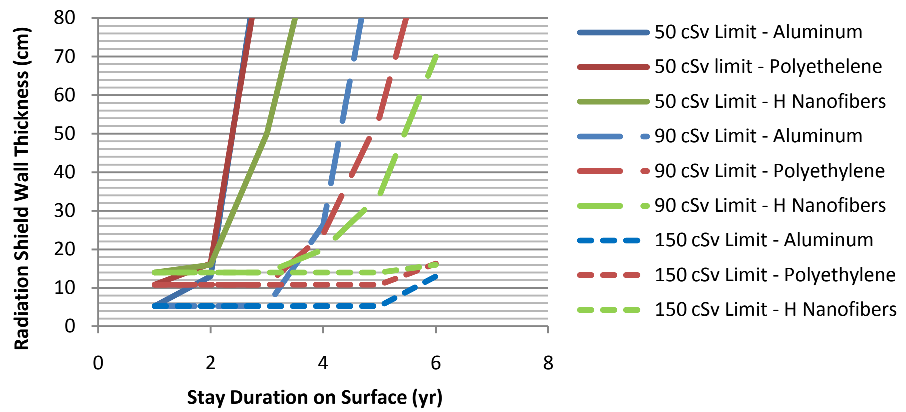

Figure 7. Required Shield Thickness Vs Stay Duration on the surface of the Moon, Ceres, or Phobos.

5. Mars & Callisto

Data gathered from several research probes and satellites gives enough information to determine the average radiation levels on Mars and Callisto. Again, this data is used to determine the required shield thickness for different durations for different materials, and is summed up in Figure 8, and Figure 9, respectively.

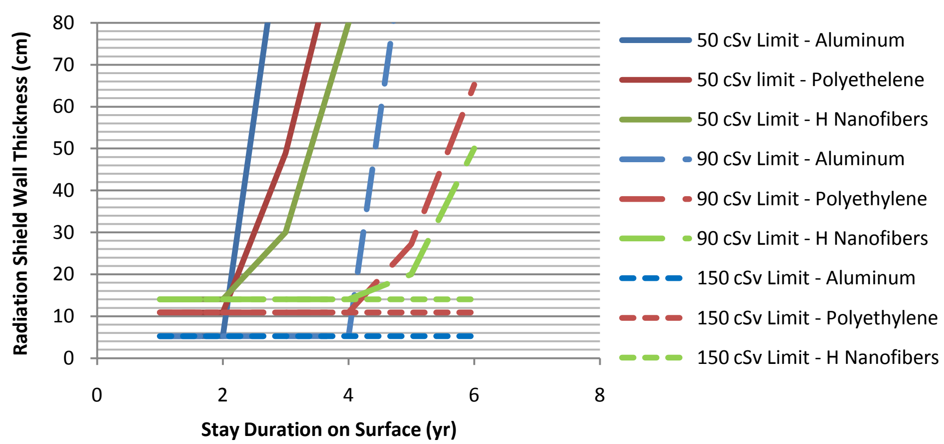

Figure 8. Required Shield Thickness Vs Stay Duration on the surface of Mars

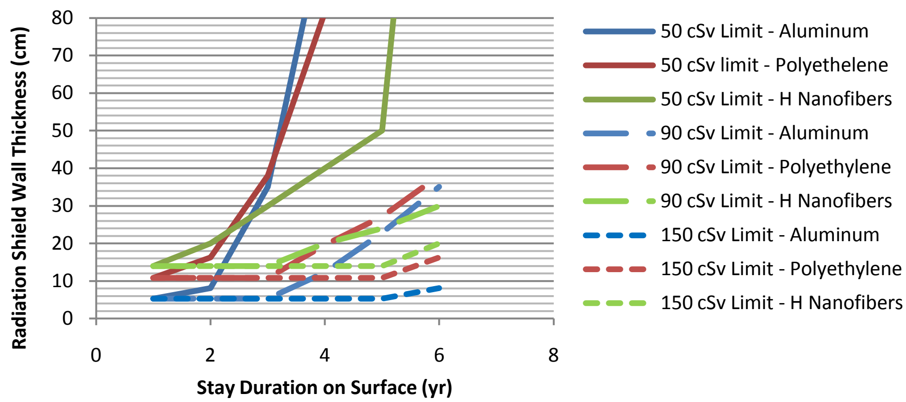

Figure 9. Required Shield Thickness Vs Stay Duration on the surface of Callisto

6. Earth and Titan

The effective radiation dose on both Earth and Titan is negligible. Therefore, no radiation shielding is required for habitation on these celestial bodies. It is expected that some radiation shielding would be required to protect the habitat en route to Titan, but this is not within the project's scope.

7. Ganymede

The Jovian moon is exposed to a large amount of radiation in comparison with every other destination considered. The moon is located within Jupiter's radiation belts and is exposed to 8 cSv of radiation per day, or 2920 cSv per year. [6] This is obviously well above any lifetime exposure limits. Therefore, it is not recommended that a crew visit this moon for more than 3 months. Even thick shielding can only reduce the exposure by a factor of 16, and severly reduces the amount of living space.

7. Radiation Shielding Requirements for Europa

Europa receives 540 cSv of radiation per day, which is far above the yearly exposure limit [f]. None of the materials researched in this paper can effectively mitigate this level of radiation. Europa is therefore inaccessible with current materials. Continuing advancements and research into new materials may allow access in the future.

8. Discussion

The radiation shielding results for the Moon, Mars, Phobos, Callisto, and Ceres show that stay times on the surface of a celestial body can be extended significantly for older crew members, as they would be less effected by radiation. Due to its structural advantages, aluminum would be the most appropriate material for short duration missions, polyethylene the best for medium duration missions, and H nanofibers would be generally be required for long stay missions.

I. Sleeping and Habitation

Sleeping and basic habitation practices depend primarily on the gravitation levels experienced on the moon or planet. In the development of a living quarter's module, there are two basic types. The first type of habitation and sleeping model would be appropriate for all of Earth's environments, as well as for the Moon, Mars, and Ganymede. This type of sleeping quarters would be like what you'd expect to find in a dorm room or other close-quartered living spaces. Beds could be bunked or cots and hammocks could be utilized. The gravity is such that people would have no problem remaining in their respective beds. In the horizontal lying position, the body can properly redistribute blood flow and relax muscles and tendons for a full nights rest and rejuvenation.

Sleeping and living in reduced-gravity environments such as on Titan, Europa, Callisto, Ceres, and Phobos, can often pose a unique problem. The gravity is not strong enough to allow a person to sleep freely on a bed, like they would on Earth. However, the presence of some gravity also does not allow a person to sleep in any orientation like they would on the International Space Station. Ideally, a person would sleep in a horizontal position. This allows the blood to redistribute within the body and for the muscles and spine to relax during sleep. However, small movements typical during Earth sleep, like rolling over or adjusting ones' arm can result in dramatic motion in reduced gravity environments if the same forces are applied. For this reason, a person would be required to be strapped to the surface on which they sleep to keep from falling off their beds. If more space is needed in the habitation module, it is possible for persons to sleep in an upright or angled position in reduced gravity and still receive a full night's rest. In microgravity, often a person only needs six to seven hours of rest to properly rejuvenate. Research is still being done in this area, but it is suggested that this is due to the increased blood flow to the brain and reduced external disturbances like waking to adjust ones' self and snoring that is often present on Earth. Opened airways and reduced pressure on the body reduces the need for these disturbances.[7]

A. Thermal Management

The thermal management study for this project consists of two aspects. First, a top-level review was conducted to assess what the maximum heat rejection needs of the spacecraft are. The generation of heat by onboard electronics and mechanical systems were considered along with heat leak from solar energy. Second, a more detailed review was conducted including a heat exchanger design and sizing.

1. Heat Rejection Study

A study was performed to determine the approximate heat rejection needs of a spacecraft traveling to the various bodies being considered. To do this, the heat flux incident on the surface of the spacecraft was calculated in Equation 4, where r is the distance from the body to the sun in meters.

$$q'' = \frac{3.81\times 10^{26}}{4\pi r^2}\ [\mathrm{W/m^2}] \tag{4}$$

The geometry of the spacecraft was then assumed to be a cylinder with a radius of 2.5 meters and a height of 5 meters. Additionally, the outer surface of the spacecraft was assumed to be covered in multi-layer insulation (MLI) with an effective emissivity of 0.02. Assuming that only one half of the cylinder receives solar thermal radiation because only half the vehicle sees direct sunlight, the total heat transfer rate into the vehicle may be found at various solar system bodies. These are tabulated and shown in Table 6.

Table 6. Absorbed Solar Thermal Radiation at Various Solar System Bodies

Planet	Incident Solar Radiation [W/m^2]	Frontal Surface Area Spacecraft [m^2]	Incident Radiation Energy [W]	Absorbed Solar Radiation [W]
Titan	14.88905607	39.27	584.6918646	11.69383729
Europa	14.88905607	39.27	584.6918646	11.69383729
Ganymede	50.0444459	39.27	1965.240795	39.3048159
Callisto	50.0444459	39.27	1965.240795	39.3048159
Ceres	177.0373839	39.27	6952.241808	139.0448362
Mars	583.5491668	39.27	22915.92219	458.3184439
Phobos	583.5491668	39.27	22915.92219	458.3184439
Moon	1354.758927	39.27	53201.25866	1064.025173

Additionally, a brief study of the International Space Station was conducted to determine, on average, how much electrical power each station module consumes. It was found that the space station solar arrays are capable of producing 110 kW of electricity. It is assumed that one of the modules considered for this project can be compared to one of the space station modules; there are currently 10 modules on the ISS. Furthermore, it is assumed that there is 100% utilization of the 110 kW produced. Finally, to determine the power requirements for the MASE module, a safety factor of 1.5 is used to account for possible advances in technology that require additional electricity. Taking all of these assumptions into consideration, the predicted power requirements for a MASE module can be calculated and is shown in Equation 5.

$$P = \frac{1.5 \times 110}{10} = 16.5 \text{ kW} \tag{5}$$

When added to the net absorbed solar radiation tabulated previously in Table 6, the total heat rejection requirements can be found. Radiator panels may then be sized based on these requirements. In particular, if a radiator on the spacecraft is assumed to have an emissivity of 0.9, then the approximate required surface area of the panel may be found via the Stephan-Boltzmann equation, Equation 6, where ε^* is the effective emissivity of the panel (0.9), σ is the Stephen-Boltzmann constant, and A_{rad} is the radiator surface area.

$$q = \varepsilon^* \sigma A_{\text{rad}} \left(T_h^4 - T_c^4 \right) \tag{6}$$

The results, showing the required total heat rejection and radiator sizing calculations are in Table 7 below.

Table 7. Total Maximum Heat Rejection Requirements and Corresponding Radiator Size

Planet	Absorbed Solar Radiation [W]	Internal Heat Generated Per Module [W]	Total Max Heat Rejection Requirements [kW]	Radiator Size [m^2]
Titan	11.69383729	16,500	16.51	52.642
Europa	11.69383729	16,500	16.51	52.642
Ganymede	39.3048159	16,500	16.54	52.730
Callisto	39.3048159	16,500	16.54	52.730
Ceres	139.0448362	16,500	16.64	53.048
Mars	458.3184439	16,500	16.96	54.066
Phobos	458.3184439	16,500	16.96	54.066
Moon	1064.025173	16,500	17.56	55.997

An approximate radiator size, assuming worst case scenario, of 56.0 m^2 is necessary to reject the waste heat of the spacecraft and to maintain thermal equilibrium. This approximation, however, assumes perfect heat transfer from the spacecraft internals to the radiator system. This assumption, of course, is not feasible. An internal heat exchanger for the spacecraft is sized in the following section.

2. Thermal Management System Sizing Study

A basic internal thermal management system was conceived and analyzed. Its purpose is to pull waste heat from onboard electronics, transfer it to the radiator system, and reject it to space. The system consists of three parts: a heat sink for the various electronics and spacecraft internals, an air/Ammonia heat exchanger, and a radiator system. These systems are diagrammed in Figure 10.

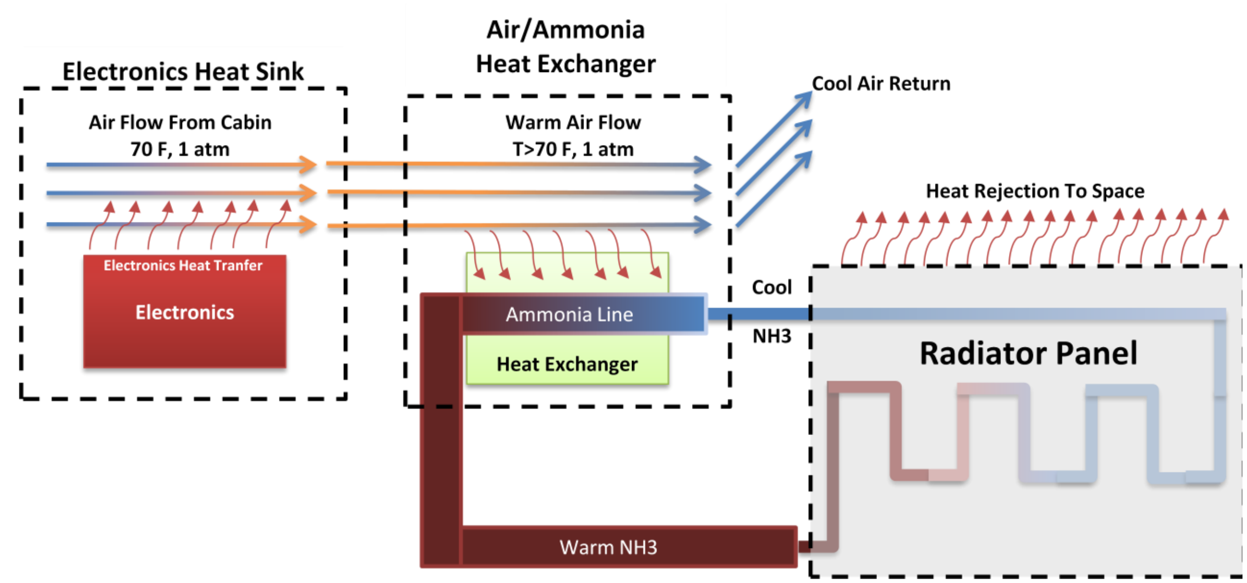

Figure 10. Thermal Control System Total System Diagram

The goal of the analysis is to size the air/ammonia heat exchanger, which is determined by the conduction area between the two fluids necessary to allow the radiator to reject the necessary amounts of heat, thus cooling the spacecraft. The following sections will discuss the basis for analysis of the three systems.

3. Electronics Heat Sink

For the purposes of this analysis, the term "electronics" will include any source of heat into the spacecraft control volume or heat generated within the spacecraft control volume. Ohmic heat generation and heat leak from incident solar thermal energy are the two primary sources of heat input into the spacecraft. Values for these sources were tabulated in a previous section.

In the electronics heat sink portion of the thermal control system, as shown in Figure 11, air from the spacecraft cabin or other sources is passed over the electronics. All of the heat being input into the system is assumed to be transferred to the air, thus a steady state temperature of the electronics is reached.

To determine the temperature of the air after being warmed by the electronics, the steady flow energy equation is used with the assumption that air may be treated as an ideal gas. This is shown in Equation 7.

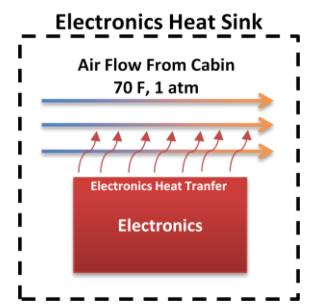

Figure 11. Thermal Control System Electronics Heat Sink

$$\dot{m}_{\text{air}} C_{\text{p,air}} T_{\text{air,in}} + Q_{\text{electronics}} = \dot{m}_{\text{air}} C_{\text{p,air}} T_{\text{air,out}} \tag{7}$$

Rearranging this equation for the temperature of the air after the heat sink, $T_{\text{air,out}}$ yields Equation 8.

$$T_{\text{air,out}} = T_{\text{air,in}} + \frac{Q_{\text{electronics}}}{\dot{m}_{\text{air}} C_{\text{p,air}}} \tag{8}$$

This analysis assumes that the temperature of the air at the start of the heat sink is 294 K, room temperature, and that the air mass flow rate, $\dot{m}_{\text{air}}$, is 0.073 kg/s, corresponding to a mean flow velocity of 1 m/s through a 0.0625 m^2 passage at 1 atmosphere of pressure. This mass flow rate was calculated based on the fact that air is presumed to be circulating from the cabin (1 atmosphere of pressure at 294 K) through various ducts that are 0.25 meters by 0.25

meters. The mean fluid velocity of 1 meter per second was selected to be on the conservative side of fluid velocities through the duct.

4. Air/Ammonia Heat Exchanger

For this analysis, the air/ammonia heat exchanger is treated as a steady flow heat exchanger with single phase fluids and and the Effectiveness-NTU analysis methodology is used. Warm air from the electronics passes over finned tubes carrying ammonia in a counter-flow set up. Heat is transferred from the air to the cooler ammonia that has returned from the radiator. This schematic is shown in Figure 12.

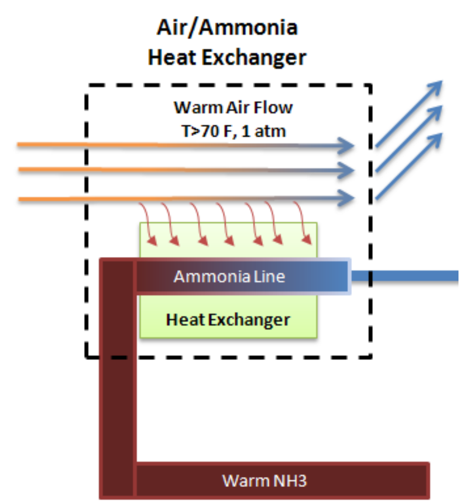

Figure 12. Thermal Control System Air/Ammonia Heat Exchanger

The NTU analysis begins by defining the maximum amount of heat transfer that can occur in the heat exchanger. This is given by Equation 9, where C_{min} is the smaller heat capacity of the two fluids and *i* represents the fluid inlet conditions. Note that because the ammonia is in a loop, the inlet temperature is based on the heat rejection that occurs in the radiator (where the incoming ammonia comes from).

$$q_{\max} = C_{\min}\left(T_{air,i} - T_{NH3,i}\right) \tag{9}$$

The heat rejection in the radiator, however, depends on the temperature of the ammonia in the radiator, which depends on the heat transfer in the heat exchanger, which depends on the heat exchanger inlet temperature of the ammonia. The solution is obviously an iterative one that is coupled with another section of the thermal management system, discussed later. Therefore, only the technique for analyzing the heat exchanger will be discussed here. A discussion on the iterative technique will follow.

The overall heat transfer coefficient, *U*, is be assumed to be a constant 800 W/m^2-K, a conservative value for air/ammonia heat exchangers. While not strictly necessary, this assumption removes the fluid mechanics from the problem, greatly simplifying the analysis.

In a typical analysis, the number of transfer units is calculated using Equation 10, where A_{hx} is the area of the air/ammonia heat exchanger under consideration.

$$NTU \equiv \frac{UA_{hx}}{C_{\min}} \tag{10}$$

However, A_{hx} is also the area ultimately being sought. In order to proceed, an initial guess on the area will be made and an iterated solution will be found. Next, the heat exchanger efficiency, ε, is calculated in Equation 11 based on correlations for a counter-flow heat exchanger, where C_r is the ratio of specific heats of the two fluids in the heat exchanger.

$$\varepsilon = \frac{1-\exp\left(-NTU\left(1-C_r\right)\right)}{1-C_r\exp\left(-NTU\left(1-C_r\right)\right)} \qquad (11$$

The net heat transfer from the system may then be found using Equation 12.

$$q = \varepsilon q_{\max} \tag{12}$$

The temperature of the ammonia leaving the heat exchanger is given by a relationship identical to that of air in the previous set of calculations. This is shown in Equation 13.

$$T_{\text{NH3,out}} = T_{\text{NH3,in}} + \frac{q}{\dot{m}_{\text{NH3}} C_{\text{p,NH3}}} \tag{13}$$

The output temperature, $T_{\text{NH3,out}}$, will be used as the inlet conditions for the radiator heat rejection system discussed next.

5. Radiator

A radiator panel affixed to the outside of the spacecraft serves as the primary means of rejecting heat to the local environment. Such a panel will be directly designed to run ammonia fluid through it, increasing heat transfer to the panel as compared to conducting heat through the panel from one end. The radiator setup is diagramed in Figure 13.

The net heat transfer from the radiator to the environment is given by the Stephen-Boltzmann equation in Equation 14.

$$q = \varepsilon \sigma A \left(T_{NH3}^4 - T_{\text{env}}^4 \right) \tag{14}$$

The temperature of the ammonia is assumed to be the inlet temperature of the fluid to the radiator. While this will over-predict the actual heat transfer by some nominal value, it also significantly simplifies the algorithm and the emissivity may be modified to partially correct for that error. It is noted that the transfer of heat from the ammonia to the panel is assumed perfect ie. no thermal gradient exists between the two. This is, again, used to simplify the analysis.

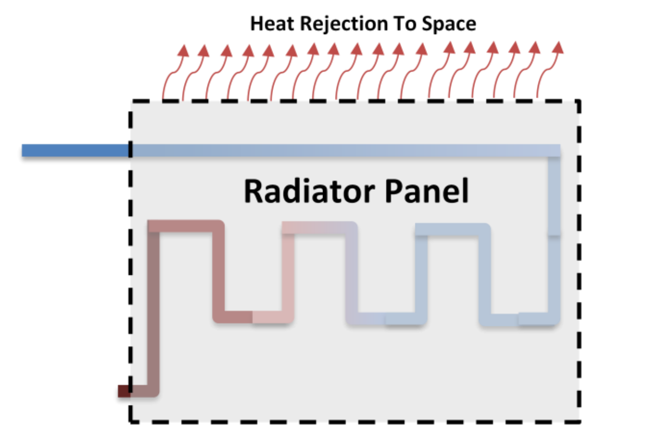

Figure 13. Thermal Control System Radiator Panel

Having calculated the heat transfer from the radiator, the exit temperature of the ammonia from the radiator is then calculated in Equation 15, as before.

$$T_{\text{NH3,out}} = T_{\text{NH3,in}} + \frac{q_{\text{reject}}}{\dot{m}_{\text{NH3}} C_{\text{p,NH3}}} \tag{15}$$

Note that the rejected heat transfer is negative (out of the system), resulting in a net temperature decrease of the ammonia, which is what is expected.

At this point, the ammonia radiator outlet temperature and the ammonia heat exchanger inlet temperature must be compared. If these values are equal, the heat exchanger area has been found. If they are not equal, then the heat exchanger area must be modified and the calculations rerun until the two temperatures are equal, as they must be, the ammonia flowing in a closed loop.

Having performed these calculations, a sufficient heat exchanger area is found to be approximately 0.25 m^2. Of course, in different environments and with different heat loads, this will vary. If this is the case, it is possible to vary the mass flow rate of the ammonia to achieve the desired cooling or heat retention based on the environment.

B. Transportation

For this endeavor, several options were investigated from current and developing transportation technologies. Functional requirements for transportation on various habitable planets or other celestial bodies were developed and used to evaluate the feasibility of potential vehicles. Departure from the planet was considered outside of the scope of this project. The initial project goals did not include investigating how the modules would be transported to the body and then onto the surface of the planets they would inhabit. Thus, it is also assumed that the development of whatever propulsion systems that were utilized to arrive at the planet would also investigate and provide a means of allowing the astronaut crew to depart the planet.

Consequently, transportation was defined as a means of enabling the resident astronauts to traverse the celestial body on which they are inhabiting (and not including the ability to depart from the celestial body). The functional requirements for this capability included the following: the ability to transport cargo, the ability to move from module to module, and the ability to explore the celestial body.

The vehicles currently being developed and tested suggested for use with this project are: Chariot, ATHLETE, Centaur, Bipedal transport (walking), cable or track driven vehicles, personal transports (Segway-type vehicles or lunar buggies), and walking/rolling modules. Pros and cons of the various vehicles were considered to determine which of the current technologies would be most suitable for this application. Chariot, ATHLETE, centaur, and scarab are all rover type vehicles (using rotating wheels as the mode of transportation).

1. Chariot

Chariot is a habitat/vehicle hybrid which acts as a sort of “mobile home” for astronauts. The vehicle acts as a pressurized habitable environment in which the astronauts can reside and also drive around exploring the planet. When a site of interest is discovered, the astronauts can exit the vehicle and further investigate the site. A photo of a prototype Chariot is shown in Figure 14.

Figure 14. Chariot Transportation Vehicle

2. Bipedal/Cable or Track driven / Personal Transports

These modes of transportation are all fairly straightforward. Bipedal is the simplest, and least expensive however, it lacks the ability to cross large distances quickly, and has limited carrying capacity Cable or track driven vehicles are also very simple however, they require a significant amount of set-up and additional infrastructure.

3. Centaur

Centaur is particularly unique because it is a vehicle that incorporates and transports a humanoid robot. It is different from the more conventional, chariot, ATHLETE, and scarab vehicles in that it is not designed to transport humans. However, due to its robotic nature, it can be quite effective at exploring the celestial body for longer periods of time with a decreased risk to the crew. Centaur does have limited payload capacity and is better designed for exploration, scientific research, and working in high risk environments.

4. ATHLETE

ATHLETE, shown in Figure 15, is an acronym for the All-Terrain-Hex-Limbed-Extra-Terrestrial-Explorer. These vehicles feature six robotic legs each connected to a wheel. This is a hybrid mobility platform that allows the vehicle to travel at high speeds on its wheels, as well as allowing the vehicle to walk, by locking its wheels and using the actuators in its robotic legs. These two transportation capabilities enable ATHLETE to traverse benign and rugged terrain with great efficiency. The Tri-ATHLETE version of this vehicle incorporates a novel design that allows it to split into two vehicles consisting of three legs each. This particular version has a payload capacity of 500kg and each half weighs approximately 720kg.[8] In lunar and other low gravity environments, the payload/vehicle mass fraction would significantly increase (e.g. on the moon the mass of ATHLETE would be about 15-20% of the payload mass that it carries). However, this is not the theoretical limit of the vehicle’s payload capacity. The vehicle is highly scalable. This vehicle can also travel at a nominal driving speed of 3 kph.[8]

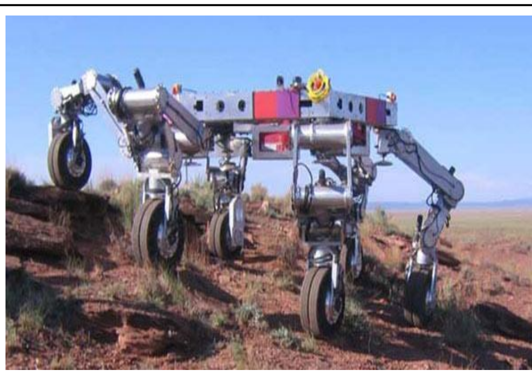

Figure 15. ATHLETE Transportation Vehicle

ATHLETE was selected as the primary transportation system for this project due to its versatility and ability to adapt to several types of terrain. Its actuated limbs also make it useful at serving an additional role of positioning and transporting entire modules. The Tri-ATHLETE system possesses the ability to attach to two ends of a module, lift it with the actuated legs and transport it to another location. All of these capabilities indicate that this vehicle would be ideal for this modular and adaptable infrastructure.

C. Travel Times and Storage

The time spent on each environment in space is a function of the time it takes to reach the destination from launch, in this case, from lower Earth orbit (LEO). To determine estimates, Hohmann transfer orbits were studied for each of the proposed destinations. In addition, the length of the mission also determines the amount of room needed for storage. The time to transfer between orbits is defined by the function in Equation 16, where r_1 is the radius of orbit of the body of departure with respect to primary body, r_2 is the radius of orbit of the body of destination with respect to the primary body, and μ is the standard gravitational parameter of the primary body.

$$t_H = \pi\sqrt{(r_1 + r_2)^3/(8\mu)} \tag{16}$$

Destinations to moons of other planets are calculated using the transfer orbit to that planet and then from the sphere of influence of that planet to its moon. These calculations, shown in Table 8, are very conservative and have times that are longer than would be foreseeable in the future when these missions would take place. With advanced technology in propulsion, slightly higher Δv's needed for Hohmann transfer orbits will be more easily achieved. For missions such as one to Titan, with an arrival time of more than 4 years from launch, it will be necessary to develop bases past LEO to make the trip feasible.

Table 8. Hohmann Orbit Times from Low Earth Orbit.

Destination	Years	Months	Days
Callisto	3	9	14
Ceres	1	3	7
Ganymede	3	9	5
Moon	0	0	5
Mars	0	8	10
Phobos	0	9	8
Titan	8	4	13

Through the NASA Advanced Food Technology, rations for one day for one person are determined to have a mass of 1.83 kg and a volume of 0.00472 m^3. This translates into 2672 kg and 7 m^3 of food storage for a 4 person crew for each year of habitation. In addition, there should be at least enough food packaged in the habitat to allow for a rescue mission the length of time of the given Hohmann orbit transfer in case of an error with the return vehicle.

D. Waste Management

Waste recycling will be key when developing a module to support life. The waste management system should be both environmental friendly and healthy. Not only this, but the method should also be cost friendly, as the price to transport water into space is $15,000 per pint.

According to NASA's Water Recovery System team, in May of 2009, the crew of the International Space Station began drinking recycled water. The average person drinks 2 liters of water per day and produces the same in urine. This waste can be recycled and used again for hydration purposes. Biological and chemical decontamination is needed to neutralization and to remove contaminants from the waste so that it can be reused.

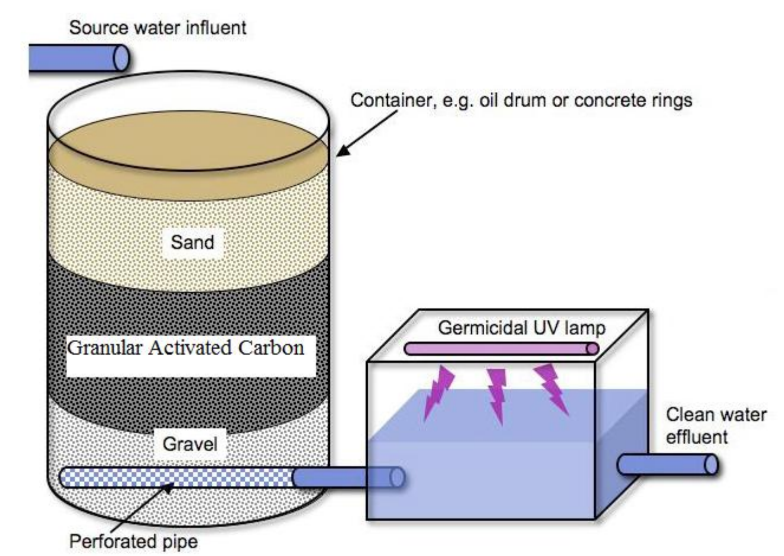

Figure 16. Illustration of Filtration System.

For biological decontamination, ultraviolet (UV) radiation is the most accurate method for the treatment of waste. UV radiation is used as a germicide. UV radiation can be obtained from the sun, or it can be provided through UV lamps. In this particular case, UV lamps would be used, as the habitats may not always be in direct sunlight. However, pesticides cannot be removed from drinking water with biological decontamination alone. Thus, chemical decontamination must be used. Chemical decontamination makes use of granular activated carbon (GAC). GAC filters out contaminants through the process of adsorption.

In the water filtration system, 5 grams of carbon are needed to purify 1 liter of water. It is assumed that a total of 6 people with a urine production of 2 liters each, would then need a total of 60 grams of carbon for the necessary filtration. Based on information given by the Environmental Protection Agency (EPA), 4.5 kg of carbon is needed to supply drinking water for 1 person for the duration of 1 year. Therefore, 27 kg of carbon is needed for a crew of 6 people per year.

The system design is shown in Figure 16. Waste flows through a tube into a container filled with layers consisting of 50 cm of sand, 60 g of GAC and 20 cm of gravel. The sand is used as a pre-filter, and the gravel is used to prevent the carbon from clogging the perforated pipes as filtered water leaves the container. Once the water exits the container, it enters another container where it is exposed to UV radiation to neutralize the contaminants: thus producing drinkable, recycled water.

E. Water Production

The water production system must be able to supply a sufficient amount of potable water, hygiene water and water for system operations (e.g. cooling electronics). Potable water will be used for drinking and cooking purposes. Hygiene water refers to water that will be used for personal activities of daily living such as showering, brushing teeth, washing clothes, and flushing toilets. In addition, water must be available to meet the needs of other integrated systems such as the oxygen production and the carbon dioxide removal systems.

Table 9. Daily Water Requirements

Number of Crewmembers	Daily H_2O Requirement (kg)
1	7.04
3	21.12
6	42.24
9	63.36

On average, one crewmember requires a mass of 7.04 kg of water daily. However, this figure can change based on crewmember activity levels required for the mission. For purposes of comparison, water requirements for varying crew sizes are shown in Table 9.

1. Water Production Technology: Fuel Cells

The most feasible method to produce water for the purposes outlined in the previous section is through fuel cells (hydrogen cells). This technology is currently employed on the space shuttle to provide auxiliary power as well as clean water.[9] Through a chemical reaction, water as a by-product of electrical power generation is made from liquid oxygen and hydrogen in a system of three alkaline fuel cells consisting of 96 cells housed in three substacks.[10, 11] These fuel cells are capable of making 11 kg of water per hour.[12]

From the fuel cells, water passes through a hydrogen separator to eliminate any trapped hydrogen gas.[2] The schematic for this process is shown in Figure 17. Excess hydrogen gas can be used in in-situ resource utilization processes or discarded overboard as waste. The water is then directed into four storage tanks, each with a capacity of 75 kg. To provide flow for use by crewmembers, the water tanks are pressurized by nitrogen. Potable water is filtered to remove bacteria and other microorganisms and can then be heated or cooled by heat exchangers for multiple uses such as drinking, food preparation or personal hygiene. Excess water produced by the fuel cells can be routed to a wastewater tank where it can be used by other systems, recycled and reused.[12]

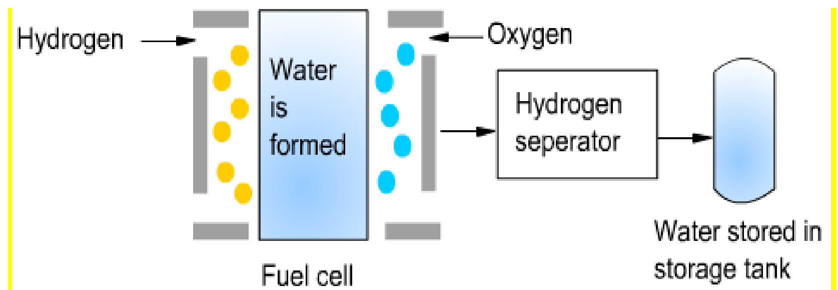

Figure 17. Diagram of Fuel Cell Water Production[3]

2. Fuel Cell Specifications

The dimension of each fuel cell is 35.6 cm inches high, 38 cm wide and 101.6 cm long. The approximate weight of each is 116 kg.

"Each functions as an independent electrical power source supplying its own isolated, simultaneously operating 28-volt dc bus. The voltage and current range of each is 2 kilowatts at 32.5 volts dc, 61.5 amps, to 12 kilowatts at 27.5 volts dc, 436 amps. Each fuel cell is capable of supplying 12 kilowatts peak and 7 kilowatts maximum continuous power. Collectively, the three fuel cells are capable of a maximum continuous output of 21,000 watts with 15-minute peaks of 36,000 watts." [11]

The fuel cells will be scheduled for routine maintenance and reused until the total accumulated time of on-line service reaches 2,000 hours (83 days). Replacement cells, if needed, will be obtained by visiting cargo space flights.[11]

V. Modular Design

One of the fundamental philosophies driving the design of these modules is to ensure that they are modular. The goal of this is to reduce complexity and cost and increase manufacturability by providing a simple repeatable modular design. All modules will possess a basic cylindrical shape with locations at the ends and on the sides to allow them to attach and interconnect with other modules. The basic interconnectivity design is shown in Figure 18. The overall mechanical structure of these modules will be identical. All modules will have common components such as radiation shielding, thermal insulation, thermal management systems, power management systems, local communication systems, etc. However, some modules will have dedicated functions such as a power module, which incorporates a nuclear power plant. This particular module will not be in close proximity to the other modules. This modular architecture will allow for the simple and effective construction of an extraterrestrial outpost. The outpost can easily be expanded as needed due to the modular and interconnected architecture. The dedication of particular modules to specific functions also provides a degree of flexibility to the outpost design. Modules can be easily modified as needed for various environments without redesigning or compromising the architecture of the outpost.

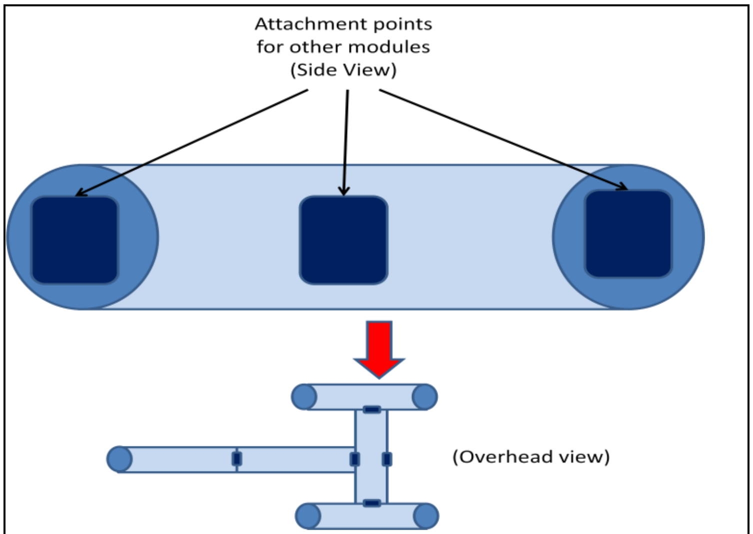

Figure 18. Cartoon of Module interconnections.

Various modular systems were identified as being crucial to the effectiveness and sustainability of the outpost. These included transportation, ISRU, air and water filtration systems, sleeping and habitation, environmental hazard avoidance, power, communications, thermal management, thermal insulation, radiation shielding, and maintenance. Although each of these particular systems will not comprise an entire module, separating them into separate is fundamental to the overall modular design. Each system can be added, subtracted or modified as necessary without affecting the other individual systems. For example a different power module can be used depending on the particular power requirements of the mission or a different ISRU model can be selected that optimizes the resources for a particular environment. Overall this design should enable exploration to be more robust and effective at adapting to the various environments of scientific interest.

VI. Outreach

NASA's mission is to pioneer the future in space exploration, scientific discovery, and aeronautics research. As pioneers, it is critical to be at the forefront of technology in these areas by using the science, technology, and engineering talent we have in our own country. Furthermore, it is essential to re-inspire young children in these science, technology, engineering, and mathematics (STEM) areas, so that NASA can be carried through to the next generation leading us to the development of amazing new technologies and to worlds beyond our own.

As young children, many of us were inspired by listening to an astronaut, learning about the moon landing, or watching a shuttle launch on TV. The idea that someday we too could work for a place like NASA and help send people into space or explore the questions of the universe, made us enter the challenging STEM fields. We feel that is our duty to inspire children the same way we were inspired ourselves. Our goal is to share our excitement with children, so that they too can be excited about science, math, and engineering and perhaps choose a STEM career for their own.

Figure 19. Academy Outreach with 3rd and 4th Graders at local YMCA

As part of our project, we included an outreach program to inspire children. We focused on finding children in the Cleveland area who may not otherwise be exposed to NASA. We visited two groups of children from local YMCA summer camps. The first group had 35 children who were in 3rd and 4th grades. The second group had 13 children who were in 5th and 6th grades. During the outreach program, we gave a short presentation on NASA, its mission, our group, and our project mission. Furthermore, we included information about our project such as possible places that could be colonized and why we'd want to live in those places. We held an open discussion with the children on things they would need to consider when living on other planets or moons. As expected, they were full of ideas including power generation systems, medical equipment, transportation, satellite systems, and others. The children also created their own activity called "stump the NASA interns" where they asked us difficult questions about complicated scientific phenomena such as black holes and the big bang. After this discussion, the children were divided into small groups and instructed to build a colony meant for the moon or for Mars using toothpicks, gumdrops, and other types of candy. Their excitement and creativity was beyond our expectations. The children had fun building the models, talking to the interns, and learning more about science and engineering. They were full of ideas and questions about what they could do to become scientists and engineers in their future.

Figure 19. Academy Outreach with 5th and 6th Graders at local YMCA

Overall, the outreach project was deemed a success. The children at the two YMCA camps were excited, inspired by STEM, and of course full of candy. We interns had nearly as much fun working with the children as the kids themselves. We recommend making public outreach a requirement in future NASA Academy projects.

VII. Conclusion

It is thought by many in the fields of science and engineering, and has been dreamed by many others in Hollywood, that humans will someday colonize worlds other than our own. It is also part of NASA's missions to be pioneers in science and technology to expand and extend the space frontier. Knowing these things, the focus of this study was to determine a way to make interplanetary habitation easier through an adaptable and inherently modular system. The requirements for survival on such planets and moons were broken down into basic functional systems. These systems were expanded and developed such that they could be fit to function in the environments of the places, we as scientists and engineers, seek to go. Research and analysis was done for each system for each celestial body in a methodical way. Then these systems are all brought back together to form basic types of modules for humans to live and work in and around. These individual modules each have the same basic structure and design, and can be interconnected in a simple way to form an entire thriving community. Many dream of colonizing other worlds. This project breaks down that dream into basic components and then re-builds it right back up in the simplest way possible, so that dream becomes a little less difficult to imagine.

Appendix A

Sabatier Reactor

This reactor uses the following reaction (see Equation 17) to produce methane and water from carbon dioxide and hydrogen.

$$4H_2 + CO_2 => 2H_2O + CH_4 \tag{17}$$

This reaction will utilize carbon dioxide found either in the atmosphere or in regolith in conjunction with hydrogen (which is brought along as cargo) to produce methane which can serve as a propellant. The water produced from this reaction could also be used directly or split into hydrogen and oxygen via electrolysis. The hydrogen is the limiting resource; however, it is very light. This reactor is especially well suited to a Martian mission due to the high carbon dioxide content of the Martian atmosphere. The Sabatier reaction itself also only requires some initial start-up energy of about 50 W and afterwards is self-sustaining; however, other components that are necessary to generate the appropriate reactants and store the methane will require about 232 W of power. The storage tanks for the hydrogen will be approximately 1 m^3.[12] Processing 50 kg of hydrogen will require 275 kg of carbon dioxide from the planet and will ultimately yield 100 kg of methane and 225 kg of water.

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